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Smoke Plumes from Large Fires

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Abstract

A large eddy simulation (LES) model of smoke plumes generated by large outdoor fires is presented. The plume is described in terms of steady-state convective transport by a uniform ambient wind of heated gases and particulate matter introduced into a stably stratified atmosphere by a continuously burning fire. The Navier-Stokes equations in the Boussinesq approximation are solved numerically with a constant eddy viscosity representing dissipation on length scales below the resolution limits of the calculation. The effective Reynolds number is high enough to permit direct simulation of the large scale mixing over two to three orders of magnitude in length scale. Particulate matter, or any non-reacting combustion product, is represented by Lagrangian particles which are advected by the fire-induced flow field. Results of the model are compared with a series of field experiments.

INTRODUCTION

There is growing interest in the environmental consequences of large fires, since the transport of combustion products by a windblown fire plume can distribute potentially hazardous materials over a wide area. Buoyant windblown plumes have been studied since the early 1960's. A summary of the early work together with a useful bibliography is given by Turner (1973). For summaries of more recent work see Turner (1985) and Wilson (1993). Virtually all the models described in these works are integral models, where the profiles of physical quantities in cross-sectional planes perpendicular to the wind direction are assumed, together with simple laws relating entrainment into the plume to macroscopic features used to describe its evolution. A great many of the models in use for air quality assessment simply use Gaussian profiles of pollutant density. Unfortunately, the plume structures actually observed are too complex to be described in terms of a few simple parameters.

Most of the assumptions required by integral models can be removed by taking advantage of the enormous advances in computational fluid dynamics that have occurred since most of these models were developed. This is especially true if it is assumed that the component of the fluid velocity in the direction of the ambient wind is literally the wind speed. The neglect of streamwise perturbations to the ambient wind is an old idea in aerodynamics, where it has been used to study aircraft wake dynamics since the 1930's (Batchelor, 1967). Once this approximation is made, the plume (or wake) can be studied as a two-dimensional time dependent entity. The large scale structure of the plume can then be determined in detail at moderate computational cost. The small scale "sub-grid" mixing and dissipation is represented with a constant eddy viscosity. This permits the mathematical structure of the Navier-Stokes equations to be retained. The effective Reynolds number, defined by the buoyancy induced velocity, plume height and eddy viscosity, is chosen to be above 10^4. Thus, at least two orders of magnitude of dynamically active length scales in all coordinate directions are permitted, leaving open the possibility of comparison with laboratory scale experiments (where the Reynolds numbers are low enough to be simulated directly). It is in this sense that the model described here is a large eddy simulation.

This approach was first used to study the settling of a smoke plume in an unstratified atmosphere by Ghoniem *et al.* (1993). That study was performed using Lagrangian vortex dynamics techniques. More recently, Zhang and Ghoniem have studied plume rise in a linearly stratified atmosphere using this methodology (Zhang, 1994). In these studies the main emphasis was on the mixing process as it affected the plume structure. The present work uses finite-difference methods to determine the large scale mixing combined with Lagrangian transport of the smoke or other pollutants. The effect of sub-grid scale velocity fluctuations on the dispersion of the smoke is accounted for explicitly, and the ambient temperature profile is subject only to the constraint that it is stable over the altitudes occupied by the plume.

MATHEMATICAL MODEL

The plume is described in terms of steady-state convective transport by a uniform ambient wind of heated gases and particulate matter introduced into a stably stratified atmosphere by a continuously burning fire. As described above, the most important assumption is that the component of the velocity in the direction of the wind *is* the ambient wind and thus is known. Since the firebed itself is not the object under study, only the overall heat release rate and the fraction of the fuel converted to particulate matter need be specified. The simulation begins several fire diameters downwind of the fire, where the plume is characterized by relatively small temperature perturbations, and minimal radiation effects. In this region the plume gases ascend to an altitude of neutral buoyancy, and then gradually disperse. The trajectory of the plume is governed by the ambient wind, the atmospheric stratification and the buoyancy induced convection. As it is not our objective to calculate the local meteorology, it is assumed that the ambient temperature profile as a function of height is available. The problem can now be reduced to the study of an equivalent two-dimensional unsteady problem in the cross-wind plane moving downstream at the ambient wind speed.

Given these assumptions, the mathematical model of a smoke plume consists of the conservation equations of mass, momentum and energy which govern the temperature T, pressure p, density ρ, and crosswind velocity components (v, w) in a plane (y, z) normal to the direction (x) of the uniform ambient wind. It is convenient to divide the temperature and pressure fields into mean background values $T_0(z)$ and $p_0(z)$ plus perturbations induced by the fire, $\tilde{T}$ and $\tilde{p}$. Similarly, the density ρ is decomposed into an ambient density ρ_0 and a small thermally induced perturbation $\tilde{\rho}$, which is related to the temperature perturbation through the equation of state taken in the small disturbance, low Mach number form appropriate to this problem

$$\frac{\rho - \rho_0}{\rho_0} = -\frac{T - T_0}{T_0} \tag{1}$$

The ambient density is related to the background pressure through the hydrostatic balance

$$\frac{dp_0}{dz} = -\rho_0 g \tag{2}$$

Assuming that the perturbations to the background temperature and density are small beyond a few diameters of the fire downwind of the firebed, we can write the conservation equations describing the steady-state plume in the Boussinesq approximation as follows

Conservation of mass

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3}$$

Conservation of lateral and vertical momentum

$$\rho_0 \left(U \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) + \frac{\partial \tilde{p}}{\partial y} = \mu \left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \tag{4}$$

$$\rho_0 \left(U \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) + \frac{\partial \tilde{p}}{\partial z} + \tilde{\rho} g = \mu \left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \tag{5}$$

Conservation of energy

$$\rho_0 c_p \left(U \frac{\partial \tilde{T}}{\partial x} + v \frac{\partial \tilde{T}}{\partial y} + w \frac{\partial \tilde{T}}{\partial z} \right) - \left(\frac{dp_0}{dz} - \rho_0 c_p \frac{dT_0}{dz} \right) w = k \left(\frac{\partial^2 \tilde{T}}{\partial y^2} + \frac{\partial^2 \tilde{T}}{\partial z^2} \right) \tag{6}$$

where c_p is the specific heat of air, k the thermal conductivity, and μ the dynamic viscosity. The viscosity and thermal conductivity are to be regarded as "eddy" coefficients whose primary role is to provide sinks of kinetic and thermal energy that are actually the result of sub-grid scale dissipative processes. This will be discussed in more detail below. The uniform ambient wind speed U is taken to be constant. For mathematical consistency, U is much larger than the buoyancy induced crosswind velocity components, and the rates of change of physical quantities in the windward direction are much slower than those in the crosswind plane. These assumptions are quite realistic several flame lengths downwind of the firebed. Since U does not change, there is no need for a windward component of the momentum equations. The details of the firebed are not being simulated, so the only information about the fire required is the overall convective heat release rate Q and the particulate mass flux. The initial temperature distribution in the plume cross section is assumed to be Gaussian and satisfy the following integral

$$\int_{-\infty}^{\infty} \int_0^{\infty} \rho_0 c_p U \tilde{T} \, dz \, dy = Q \tag{7}$$

The particulate matter (or any non-reacting combustion product) is tracked through the use of Lagrangian particles which are advected with the overall flow. The initial particulate distribution mimics the initial temperature distribution. If either more detailed experimental data or the results of a local simulation of the fire bed dynamics is available, then these could be used in lieu of the Gaussian profile.

Details of the numerical methodology used to solve the above equations are given in Baum (1994). Briefly, the steady-state, three-dimensional equations are written as a two-dimensional initial value problem where the windward spatial coordinate x is replaced by a pseudo-temporal coordinate. Figure 1 shows the results of a sample computation, illustrating the position of the initial slice and the extent of the computational domain. The plume is visualized by interpolating the particle locations onto the computational grid, and then

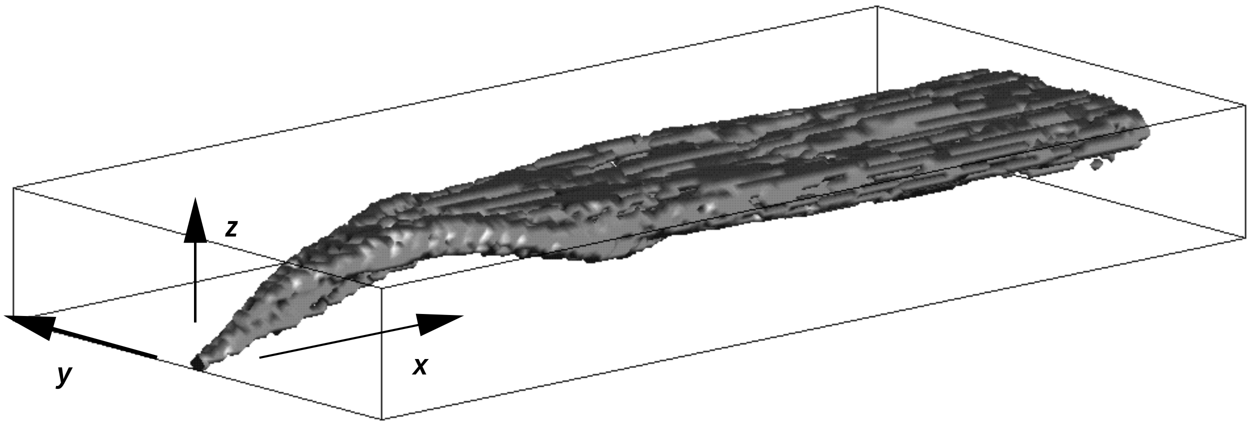

FIGURE 1: Results of a sample calculation showing the visible extent of the smoke particulate from a large fire. The length of the viewbox is 8 kilometers, the height is 1 km, and the lateral extent 4 km. The wind speed for this example is about 6 m s^{-1}, the stratification height is roughly half of a kilometer, and the heat release rate for the fire is about 200 megawatts (MW).

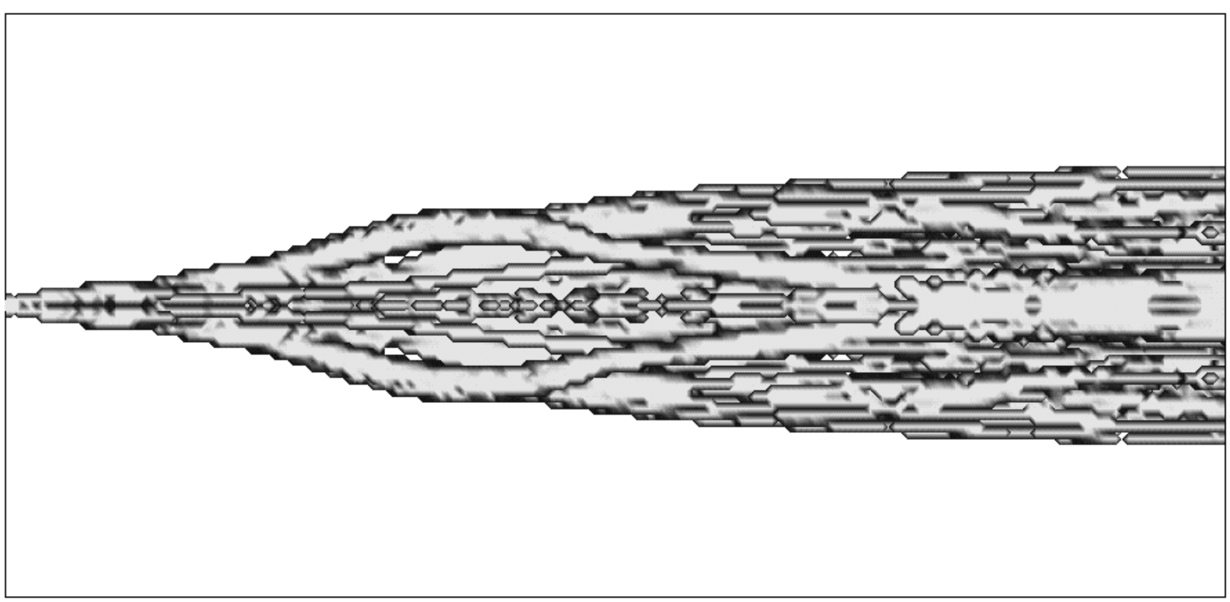

FIGURE 2: The plume shown in Fig. 1, shown from below. Note the two counter-rotating vortices that entrain most of the fresh air into the smoke plume.

FIGURE 3: Photograph taken from about 200 m downwind of the Newfoundland Offshore Burn Experiment (NOBE) showing the two large counter-rotating vortices which characterize the structure of the rising smoke plume.

FIGURE 4: Aerial view of second Alaska Clean Seas emulsion burn experiment, Prudhoe Bay, Alaska, September 1994.

plotting the isosurface on which the particulate density is a chosen value. An interesting view of the plume shown in Fig. 1 from underneath is shown in Fig. 2. From this perspective, one can observe the two large counter-rotating vortices which entrain much of the fresh air; mixing with and cooling the combustion gases. These vortices are readily observed in actual large scale experiments (See Fig. 3).

RESULTS

In early September 1994, Alaska Clean Seas conducted at their Fire Training Ground in Prudhoe Bay, Alaska, three mesoscale burns to determine the feasibility of burning emulsified oil. An aerial photograph of one of the burns is shown in Fig. 4. Each burn consisted of burning an oil mixture within the confines of a fire-resistant circular boom which floated in a pit filled with water. The boom diameter was roughly 9 m, and the rectangular pit was roughly 20 m by 30 m. The first and third burns consumed emulsions of salt water and 17.4% evaporated Alaskan North Slope (ANS) crude. Emulsion breakers were applied to these mixtures. The second burn consumed fresh ANS crude. Heat release rates for the three burns were estimated to be 55, 186 and 98 MW, respectively. The mass flux of particulate was based on a smoke yield for ANS crude of 11.6%.

At the request of the Alaska office of the US Environmental Protection Agency, the EPA's Emergency Response Team (EPA/ERT) came to Prudhoe Bay with 12 MIE real-time aerosol monitors (RAM-1). These instruments employ a sensing principle that is based on the detection of near-forward electromagnetic radiation in the near infrared. The amount of scattered radiation detected quantifies particulate and aerosol concentrations. The twelve instruments were set out on tripods, spread out in rows of three or four, at distances ranging from 1 to 5 km from the burn site. The deployment strategy varied from burn to burn, depending on the weather conditions and the terrain over which the plume was expected to loft. The instruments were set to sample every second, and then log the 5 second average. Global positioning instruments recorded the locations of the individual devices. Atmospheric temperatures, wind speeds and wind directions were measured with a weather station suspended from a small tethered blimp, deployed just after the burns were completed.

Figure 5 summarizes the results of the experiments, showing the model prediction of ground level particulate concentration versus the actual measurements made in the field. The field measurements were averaged over the time of the burn. Neither the model predictions nor the RAM data were uniform in space or in time, due in part to random fluctuations in wind direction, convective cells which are not accounted for in the model, small terrain effects, and unsteady burning of the fuel. Nevertheless, the agreement between the time-averaged model predictions and field measurements are quite good, showing particulate concentrations ranging from 0 to 80 μg m^{-3} along the narrow path over which the plume is lofted. In addition to ground level instruments, a small airplane was hired to fly in the vicinity of the plume and record plume positions at various times, as well as to photograph the burn site and the plume. According to flight track data, the plume from the first burn rose to a height of about 550 m and the plume from the second burn rose to about 400 m. These measurements are in very good agreement with model predictions, based on atmospheric profiles obtained with a helium blimp and a helicopter. The visibility on the day of the third burn was very limited, and all aircraft were grounded.

CONCLUSION

The model of plume dispersion presented above is best described as a large eddy simulation valid in an intermediate region downstream from the fire. This region begins a few tens of meters from the fire and extends a few tens of kilometers downwind. Nearer to the fire the temperatures are high, the radiation field intense, and the Boussinesq approximation is not valid. Also, the approximations which allow replacement of a three-dimensional steady plume by a two-dimensional time dependent one are not valid near the fire because the buoyant velocity of the plume is comparable to the ambient wind speed. Further than a few tens of kilometers downwind of the fire, larger scale meteorological effects begin to dominate, and flat terrain, steady wind assumptions break down. However, within the limits of applicability, the present model offers a high resolution representation of a smoke plume that is consistent with both the current understanding of plume dynamics and with experimental data. Moreover, the computations reported here are well within the range of current generation workstations (where in fact they have been performed). It is hoped that future work will improve the current capabilities of the model.

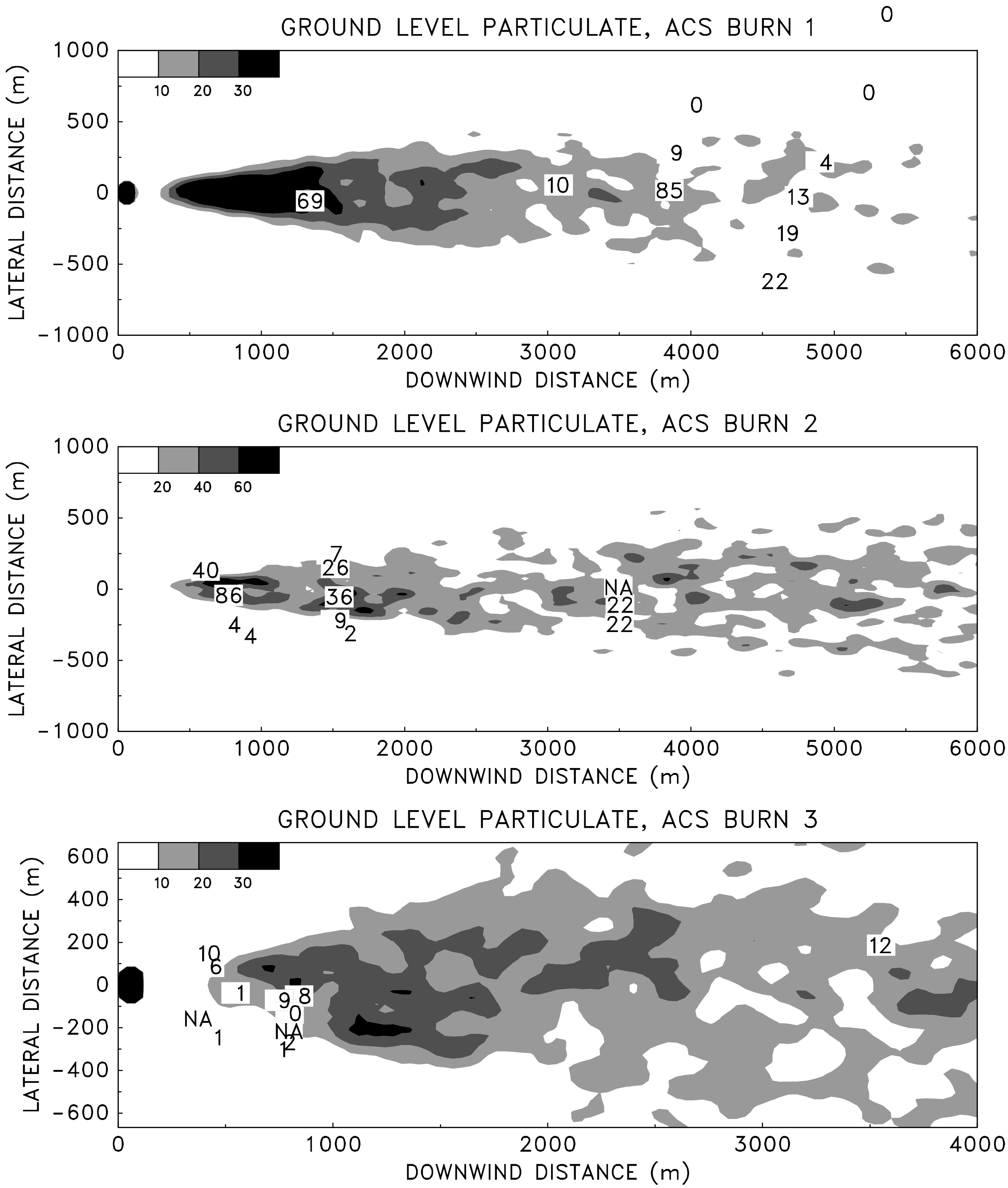

FIGURE 5: Predicted ground level particulate concentrations from the LES model (shaded contours) along with actual time-averaged RAM data for the three ACS Emulsion Burns (numerical labels). All concentrations are given in units of μg m^{-3}.

The comparisons between the field experiments and the predictions of the LES model show good agreement given the uncertainty of the input parameters. This favorable comparison suggests that the uncertainty of the model prediction is commensurate with the uncertainty of the input parameters, and that the limitations resulting from the physical assumptions of the model are outweighed by the uncertainty of the input parameters.

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Discussion

Yoshihiko Hayashi: Thank you. In connection with the very last slide, you said that you have conducted rather extensive calculations with regard to mesh intervals. I'm sure there is some limitation in terms of the capacity of the calculated errors and so forth. But how did you go about it in terms of measuring the first mesh intervals of the smoke plume?

Kevin McGrattan: That's a good question. Without getting into too much detail that people may not appreciate: If you look closely at this slide, you can see the mesh buried underneath the terrain. The spatial resolution of this calculation is on the order of 100-150 meters. The reason why we chose this resolution is that for Alaska, the terrain data that is available via the United States Geological Survey is roughly on the order of 200 meter resolution. So there is no point in doing a more finely resolved calculation if we don't know the terrain better to 200 meters.

Yoshihiko Hayashi: In this calculation, you took into consideration of the complexity of the terrain of various areas. Is it common practice that when you make this kind of calculation, terrain factors are always taken into consideration?

Kevin McGrattan: No. In fact, most atmospheric dispersion model available today are based on much simpler principles. The current models which are known as Gaussian models, maintained by the Environmental Protection Agency, are basically empirical correlations based on the notion that plumes spread in a Gaussian factor. These models, because they are very simplistic, do not usually account for terrain. So much of what we are doing here is relatively new because of the fact that the computers that we have available to us are powerful enough to resolve the plume at resolutions that we think are important.

Hiroshi Koseki: First of all, I would like to express my appreciation that I had a very precious opportunity of participating in some of the research activities in this area, as Mr. Mulholland mentioned in his presentation two days ago. I understand that you have been examining the spread of smoke plumes produced by various fires. And I also understand that those smoke plumes tend to have very extensive distribution. When you examine the movement of smoke plumes, do you also look at the different sizes of the smoke or the magnitude of smoke?

Kevin McGrattan: Yes we do. In fact, a lot of the measurements that Doug Walton has made and that you have made, involve the distribution of particulate size from these fires. We generally assume, based on measurements made with cascade impactors, that the smoke particles are on the order of ten micrometers or less. This is what in this country is call PM10 particulate, and this is the form of the particulate that gets into your lungs and is most harmful. Because the particulate is relatively small, its deposition is not important in relation to the overall convective motion of the air. In other words, the time scales that we're looking at show very little deposition of the PM10 particulate. So to answer your question very simply, once we know the smoke yield, we assume that that smoke is all being convected with the plume, and the calculation does not discern the various sizes of the particles. As long as we're assured that it's roughly on the order of ten microns or less, we treat it as a passive scalar. I've mainly talked about smoke because for these crude oil fires, it is the smoke that is considered most harmful. However, there's nothing that prevents us from considering any other passive quantity produced by the fire. These calculations will work equally well for benzene, SO_2, or whatever else you could think of.